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**Field Calibrations of Three New Asbestos
Fibre Measuring Techniques,
with the existing methods,
in Quebec Asbestos Mines and Mills**

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MICROMEDIA

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Abstract

The asbestos prototype developed by Metrex, achieved a sensitivity of 0.2 fibres/ml. Further work, in preparation for on-site testing in a Quebec asbestos mine, in which we concentrated on a computer storage and energy-saving timing control, did not result in improvements of the original prototype sensitivity.

It is proposed to develop a prototype with a sensitivity in the range of 0.05 to 0.1 fibres/ml, using a newly developed semiconductor laser along with an innovative optical system.

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1.0 INTRODUCTION

Before the present stringent monitoring and control measures in asbestos mills and mines were put in place, the exposure of workers to airborne asbestos particles resulted in serious respiratory ailments. Since the seventies, the legislation in place allows exposures to concentrations not higher than about 0.1 to 5 fibres/ml. The practically total absence of respiratory ailments in new workers exposed only to these lower concentrations, allows us to conclude that a controlled safe use of asbestos, especially of the types mined in Quebec, is possible.

The detection and measurement of the concentration of airborne fibres is obviously a crucial requirement in any industrial protection program in order to assess potential dangers and enforce the regulatory laws. The only method, presently accepted for the determination of the asbestos concentration, consists of counting and sizing of fibres by phase-contrast microscopy of samples collected by filtration on membrane media. The accuracy of this method suffers due to the subjectivity of human interpretation, but primarily, the process involves significant and in many cases, intolerable time delays before the information becomes available and can be used for the implementation of corrective or protective measures.

The present fibrous monitor is intended to measure the concentration level in real time and to provide not only the level of concentration, but also a warning of equipment failure or sudden changes in the concentration due to certain maintenance operations or changes in ventilation patterns. The monitor has to be reasonably inexpensive so that a number of units can be

placed in a mine to provide the total picture of human exposure. Also, the monitor must exist in a portable version, which will aid supervisory personnel in the detection of unsuspected sources of particles. As an example, very high concentrations were obtained by cleaning an electric motor using compressed air and stirring up the fibres sedimented inside the housing.

The goal of the present project was to produce several asbestos monitors and calibrate them in an asbestos mill through comparison with other available methods, in particular, with the filtration method. Before the units were manufactured, the system had been redesigned, to include one week computer storage of data and energy saving features, in order to minimize the battery size.

2.0 Principle of Operation

2.1 Optical System and Light Scattering

The operating principle of the optical system is shown in Fig. 2.1. Two light emitting diodes (LED) radiating narrow beams of infra-red radiation centred around $0.9\text{ }\mu\text{m}$, illuminate a rectangular opening (approx. $8\text{ mm} \times 5\text{ mm}$). On the top and bottom edges of the opening are two high-voltage electrodes for fibre alignment. A lens projects an image of the opening onto a mask in front of the detector. The mask also has a rectangular opening, which is slightly smaller in size than the image of the main opening. Light passing through the mask reaches the silicon detector connected to a synchronous detection amplifier, tuned to the frequency of the LED modulation.

In the absence of dust and fibres, no scattered light can reach the detector. The edges of the opening at the electrodes will diffract light, which cannot be detected because the edges are imaged beyond the mask opening. The detector only sees a uniform background inside the light trap. Some light from the LED is reflected from the partition, back into the horn and finds its way to the detector. This offset can be alleviated by removing the horn. However, the sensor would then react to the presence of objects such as people who are closer than, say, 50 cm from the instrument.

Particles suspended in the vicinity of the partition are illuminated by the two LEDs. Some of the light scattered by these particles is collected by the lens on the mask and reaches the detector. The amount of scattered light received from any individual particle is a function of the positioning of the light sources (angle α , Fig. 2.1), size, shape and refractive index of the

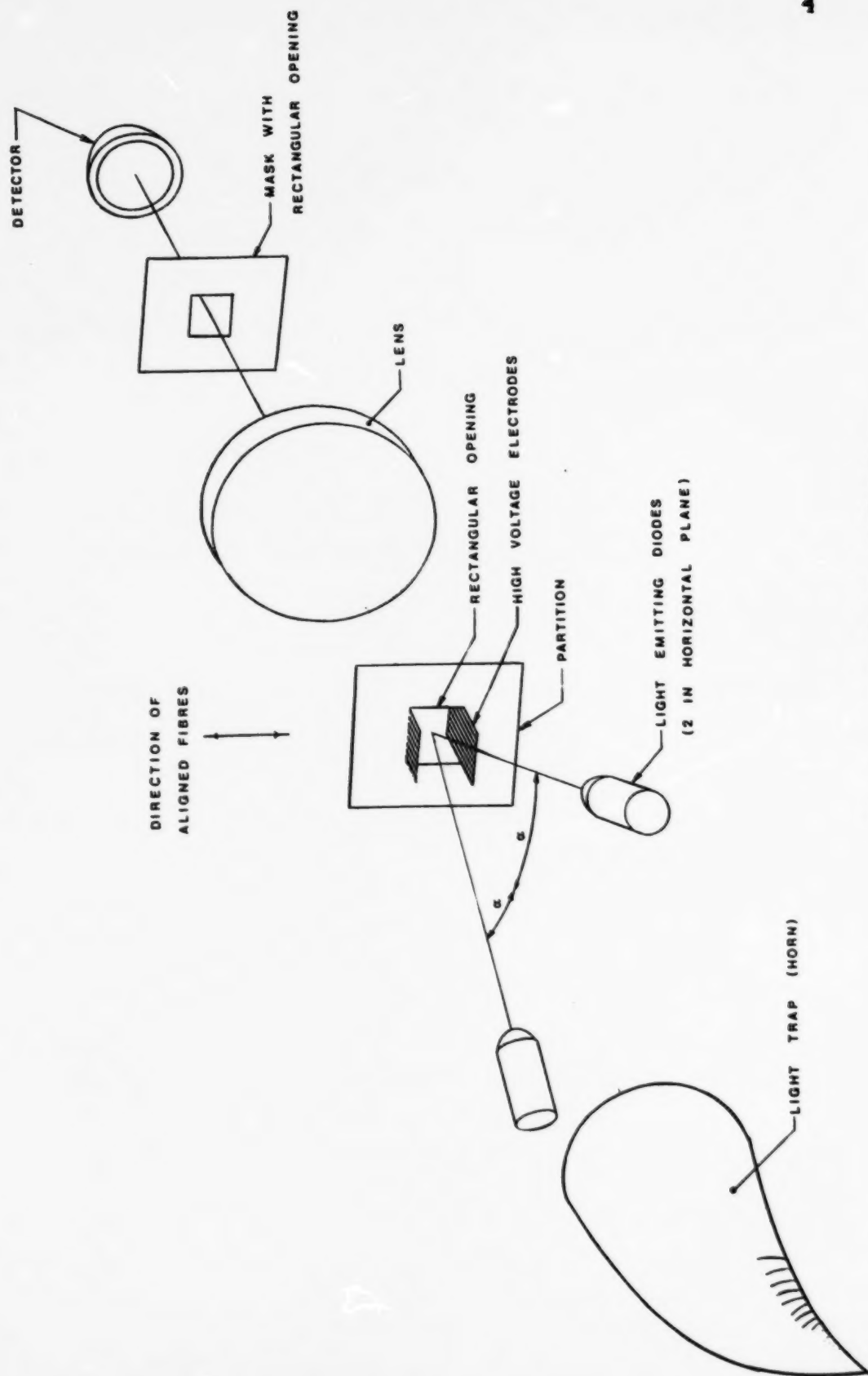


Figure 2.1 Optical System

particle, size of the lens and overall geometry. In the presented geometry of the sensor, asbestos fibres scatter a large amount of light to the detector if they are aligned vertically, while for any other alignment they send much less light in the direction of the detector.

The fibres are aligned by means of high voltage applied to the electrodes. With a potential of about 1000 V/cm, the alignment is nearly complete, while for smaller potentials the efficiency of alignment decreases. The frequency of the field is about 10 Hz. (The main electrodes are on for 0.05 seconds and the disalignment pins are on for the next 0.05 seconds). In order to be able to use a small and convenient high voltage transformer, the applied field is not DC, but AC with a frequency of about 10 kHz.

The electronics extract the asbestos signal by detecting the changes on the photodetector output, synchronous with the electrode switching frequency. The 10 Hz modulation of the signal is proportional to the asbestos concentration, while the overall signal level is proportional to the concentration of dust.

The described signal processing has the advantage of using a single channel for both measurements. Many sources of error are thus eliminated or cancelled out. However, a disadvantage of the process is the fact that the "on" and "off" signals are not taken at the same time. As a result, for a signal which strongly fluctuates with time, the difference (corresponding to asbestos) varies widely and can even be negative. To minimise the fluctuations, a time constant of 3 to 5 seconds is placed on the output.

The electronic amplifier utilizes the synchronous detection principle, thus achieving a very narrow band and excellent rejection of any light which is not modulated with the chopping frequency of the system. The LEDs are modulated electrically, and no mechanical modulator is required.

2.2 Fibre Alignment

It has been shown and derived in our previous reports that an asbestos fibre in an electrical field polarizes, and the interaction of the field and bound charges generate a moment tending to align the fibre with the field lines. As shown in Figure 2.2, the moment is zero for the fibre parallel or perpendicular to the field and maximum for about 45° tilt against the field. The magnitude of the aligning moment is proportional to the field strength squared and to the fibre volume.

The drag moment, braking the motion of the fibre, was shown to be proportional to the angular speed and the fibre dimensions. The Reynolds number of the motion is very low.

The moment of inertia and the corresponding acceleration moment are totally negligible in comparison to the field and drag moments.

A rotating field was investigated and the fibre follows the field rotation with a slip (lag) from zero to about 45° . The lag is a function of a single dimensional parameter: the length/diameter ratio. Table 2.1 lists the results of computations showing that if a field rotation of 5 Hz is chosen to become independent of turbulent fluctuations of the underlying dust, and if we want to rotate a fibre of $L/D = 200$, then the field strength must be 4.8 kV per cm.

$$D = 2 \times 10^{-6} \text{ m}, \quad L = 10^{-5} \text{ m}$$

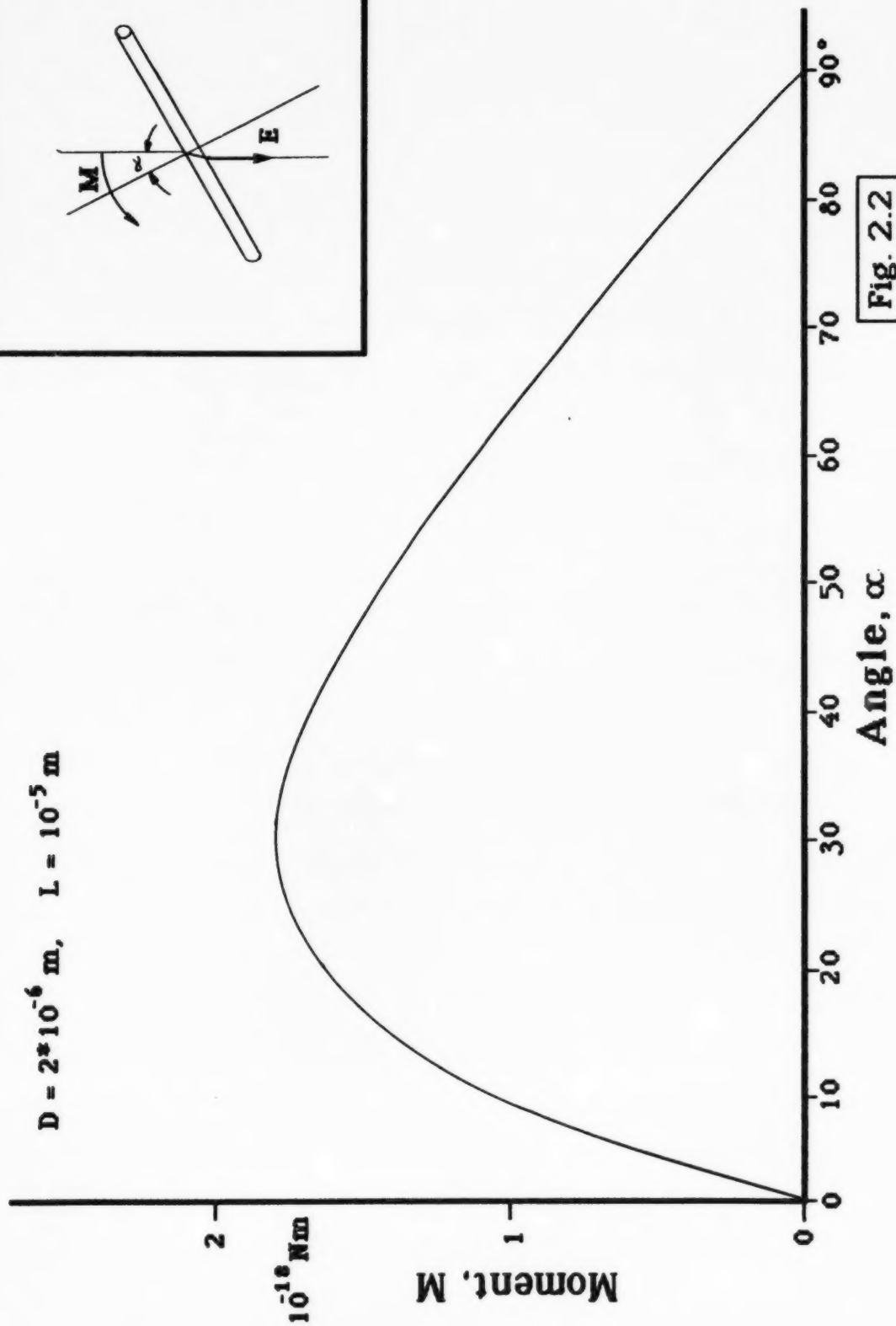


Fig. 2.2

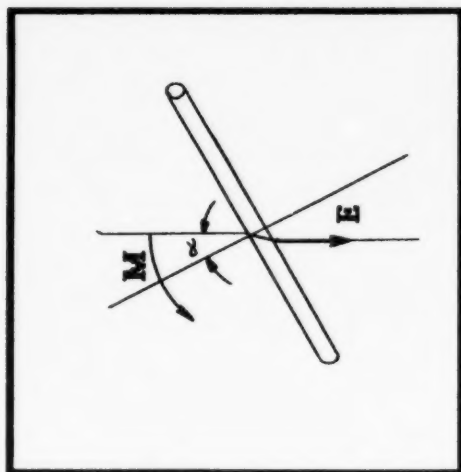


Table 2.1 Field Frequency (Hz) the Fibre Can Follow

fibres L/D field	L/D = 25	L/D = 50	L/D = 100	L/D = 150	L/D = 200
$E = 1.2 \text{ kVcm}^{-1}$	14	4.45	1.29	0.630	0.351
$E = 2.4 \text{ kVcm}^{-1}$	55	17.8	5.16	2.52	1.4
$E = 3.6 \text{ kVcm}^{-1}$	125	40	11.6	5.67	3.16
$E = 4.8 \text{ kVcm}^{-1}$	223	71	20.6	10	5.6
$E = 6.0 \text{ kVcm}^{-1}$	350	111	32	15	8.7
$E = 7.2 \text{ kVcm}^{-1}$	500	160	46	22	12

3.0 Conceptual Design of First Prototype

In order to provide a sensitive monitor which would be inexpensive and therefore available in quantities for use in the mine, several new conceptual ideas have been introduced into the design of the light scattering instrument.

Natural drafts and diffusion of the particulate cloud are used for transporting the sample into the active volume of the detector. As a result, no pumps, fans or pipes are required and the aerosol is monitored in its natural undisturbed state. Extensive testing proved that the propagation of the aerosol cloud is fast enough so that the response to any event can be achieved within a second or two. Since no air sampling channels are required, the monitor head is relatively small and can be easily placed on a worker's helmet or placed very close to the potential source of the aerosol.

The instrument senses the average concentration of fibres per ml without controlling the flow of air. Thus, if the flow of air happens to be fast, the residence time of the fibre in the sample volume will be short, but many more fibres during a unit of time will be transported into the sample volume and monitored. Thus, the output signal will be independent of the air speed, presenting always the mean concentration per ml.

The asbestos fibres are distinguished from an ordinary background dust by their distinctive scattering pattern. Basically, a fibre placed in a narrow beam of light is known to generate a sheet-like scattering pattern perpendicular to the fibre axis. If the fibre is made to rotate, the sheet of light would rotate with it and change illumination of the detector placed outside the main optical beam in the forward direction. On the other hand, ordinary, more or less spherical particles of dust possess a scattering pattern

which is practically uniformly distributed in the forward direction. The optical system, to distinguish between the two types of scattering, is based on the use of LEDs, since at the time of the instrument design, the semiconductor laser was too costly for this purpose. It is, however, necessary to design the optical system in such a way that it allows the use of LEDs, although they are less narrowly focused than laser beams. The design of the system fulfills this requirement. It has a system of apertures, which shield the lens of the detector from the direct illumination by the LED, and also, it has a sophisticated system of light traps that absorb the excessive radiation reflected from the internal walls of the monitor. As a result, the detector looks through the sample volume into a dark background of an absorbing light trap, receiving a very low background offset illumination. On this dark background, the individual pulses of light scattered from particles passing through the beam of the LED are clearly distinguishable with a good signal-to-noise ratio. The alignment of the fibres initially presented what seemed to be a problem of switching the high voltage "on" and "off" with relatively low frequency which the fibres could follow, but at the same time requiring a physically very large transformer for this low frequency, in the area of 5 to 10 Hz. The arrangement which resulted from our experimentation is simple and highly efficient. A chopper feeds a small ferrite transformer with a frequency of the order of 10 kHz, making the process of conversion into high voltage very efficient. This high frequency - high voltage is switched between the main electrodes and two disaligning pins with a frequency of 5 to 10 Hz. The process of fibre alignment can then be described as follows: The high voltage polarizes the fibre and pulls it into alignment parallel to the field direction. (Let us assume that the fibre is tilted initially 45° against the field direction). However, with a frequency of

10 kHz, the field reverses its polarity. This new field instantly, without any noticeable time delay, re-polarizes the fibre and the resulting force pulls the fibre again into the original direction, trying to align it again parallel with the field. As a result, the fibre is getting closer and closer to the alignment direction with each period of the high frequency field application.

To bring the fibres out of alignment, it is not sufficient to depend on the Brownian motion and air motion to bring the fibres into random positions. It is necessary to apply the field in a direction tilted roughly 45 or 60° against the original field. The angle is not 90° because the moment aligning the fibre, as we derived previously, is zero for a relative fibre direction to the field of 0° and 90°. Therefore, if we align the fibres in the main direction and try to disalign them with a field oriented at 90°, the fibres would respond only slowly, being brought into motion by a random deviation from their exact 90° position. However, if we try to re-align the fibres with a field oriented at 45°, they respond very quickly because the initial moment is very large. The choice of angle of the disalignment pins depends also on the numerical aperture of the detector lens. Visualizing a sheet of light attached perpendicularly to each fibre rotating across the circular aperture of the lens, we can see that the fibre motion must be larger than at least half of the lens' relative size, so that with certainty, all the scattered light is brought out of the receiving angle of the lens. Considering that some fibres are not totally straight, but slightly bent, it seems to be advantageous to choose the angle between the main electrodes and the disalignment even larger than 45°, so that the scattered light will be moved from the detector lens, even if some of the fibres are twisted and bent.

In the field monitor of our type, we are concerned with the detection of the presence of fibres rather than an exact categorizing according to their

dimensions. However, the alignment by the electrical field presents a possibility to separate the fibres by the ratio of length to diameter. As we have shown previously, the response of the fibres to the electrical field is a function of a single parameter, that of the length/diameter. Relatively long and slim fibres respond more slowly to the electrical field, while short and thick fibres respond fast. The separation of the fibres according to the L/d ratio can be achieved in two ways, by changing the field strength and field lag. The field lag, especially, presents a simple method of discarding very short fibres which correspond to length less than 3 to 5 μm , not counted in the standard membrane filter method. Since these fibres are oriented first, it is sufficient to postpone the optical detection to an element of time when the field has been "on" for a set time. This technique would also eliminate sensitivity to non-spherical mineral dust, or at least minimize it. Although all these possibilities seem to be interesting enough, the instrument is meant to monitor fibrous material in locations where asbestos is being manipulated and thus the composition and type of fibrous material are known. In situations where this is not the case, the optical method can always be supplemented by the membrane filter testing to establish the composition. The monitor gives also the real-time information regarding the source of the particles, and the relation of concentration in the environment to various activities.

The simplicity of the instrument resulted from the design of the optical system, which allows an integration over a wide range of parameters. For example, the scattering from a particular fibre is received for the fibre position in the sample volume changing from one edge of the optical aperture, through its middle to the other edge, thus continually changing the scattering angle received by the detector. The detector lens has a relatively

large aperture, thus receiving a large solid angle of scattered light and integrating the various scattering maxima and minima within this angle. The illuminating LED light is by no means monochromatic, and the scattering is again integrated over an entire range of wavelengths. The divergence of the light source is in the vicinity of $\pm 6^\circ$, creating a non-parallel illuminator. Also, at any particular time, a large number of particles can flow through the sample space. All these "wide band" parameters contribute to the increase in sensitivity of the device. They in no way interfere with the reproducibility of the measurement, as long as we are not interested in identifying parameters of an individual fibre. The use of a combination of these many "wide band" parameters resulted in a powerful detection technique presenting results comparable to much more expensive instruments suitable only for an occasional sampling or for laboratory use.

The analog signals from the monitor represent the concentration of asbestos fibres and the total concentration of dust plus asbestos in the workplace. These two signals can be presented in any desirable manner. The present instrument has a memory board storing the concentration values measured every 3 or 4 minutes. At the end of the shift, these concentration values can be discharged through any commercially available micro-computer and printed. For monitoring of instantaneous changes in concentrations, the instrument is also equipped with BNC connectors for an analog recorder.

The zero stability of the instrument, especially of the asbestos signal, is very good. Since the technique used compares the optical scattering when the field is "on" and "off", this basically differential method eliminates automatically, many sources of drift which might originate in the electronics due to temperature changes, etc. As a result, the calibration of the span

(system sensitivity) is not normally required and can be accomplished from time to time in testing chambers. On the other hand, the zero line calibration should be performed regularly, since the zero drift line would be immediately misinterpreted as a concentration reading. The calibration can be accomplished using an air cylinder of relatively small size carried by the maintenance personnel, who would reset zero by depressing a button while providing the clean air.

3.1 System description

The optical part of the sensor is shown in Fig. 3.1. The LEDs (1) illuminate an aperture (2) which carries a pair of main electrodes and a pair of pins tilted about 60° to the plane of electrodes. The main electrical field between electrodes is oriented perpendicularly to the page in the upper part of Fig. 3.1. An aligned fibre is therefore also oriented perpendicularly to the page. An illuminated fibre creates a sheet of scattered light in the plane of the page, which intersects the detector lens (3), and increases the signal above the level corresponding to the random orientation of fibres and to dust present with the fibres. The electrodes are placed on both sides of the aperture (2), to increase the width of the field and the efficiency of the alignment.

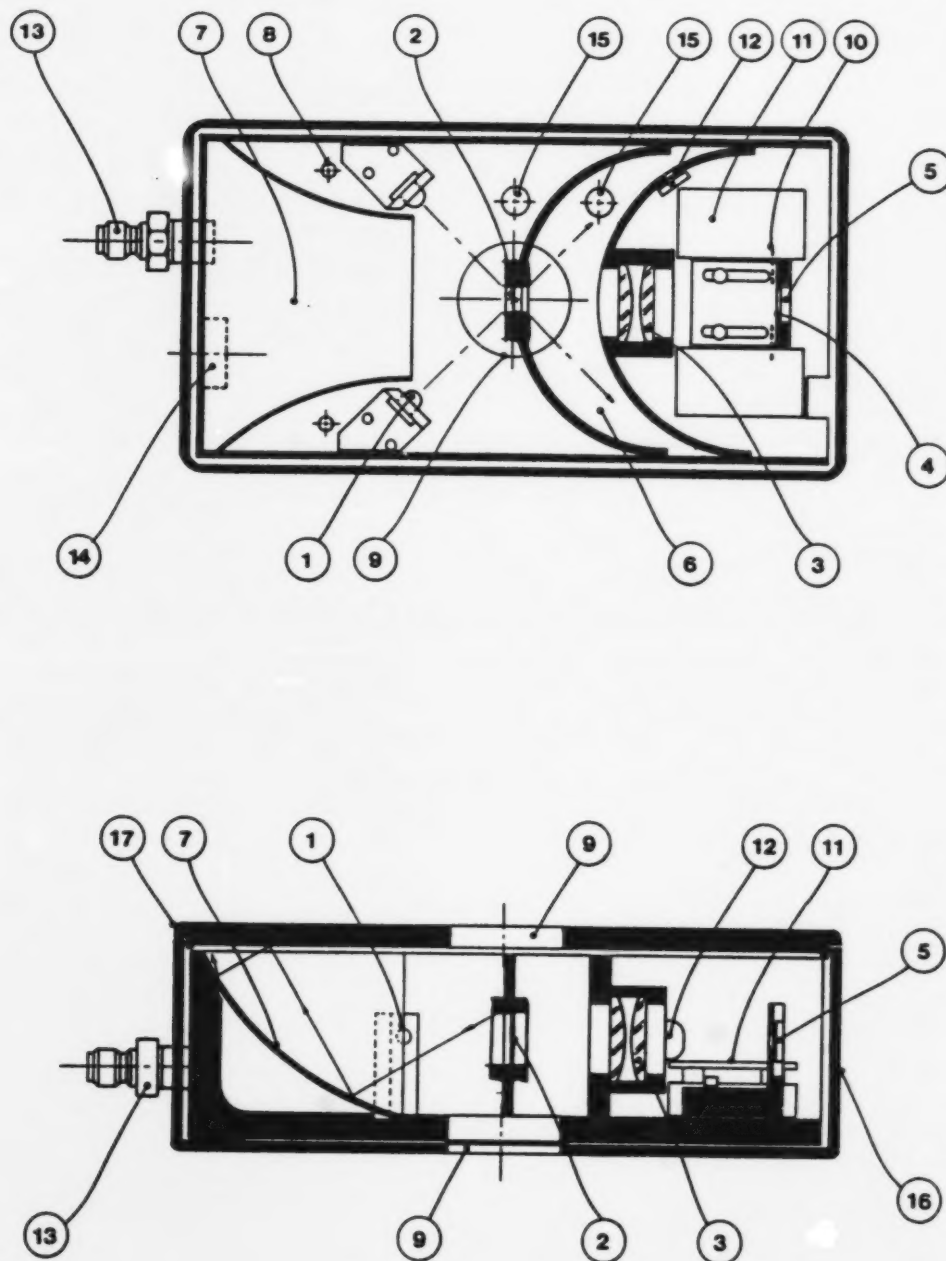


Figure 3.1 Asbestos Monitor

3.2 Electronics Description

The block diagram, shown in Figure 3.3, consists of three major parts:

- a) Electronics
- b) High voltage transformers
- c) High voltage electrodes

A high frequency (HF) oscillator produces an adjustable frequency between 4 and 10 kHz. This frequency is brought to the modulator where it is chopped to one of the two high voltage transformer drivers. The chopping frequency is generated by a low frequency (LF) oscillator and is adjustable between 3 and 100 Hz. High voltage transformers convert low voltage signals into high voltage signals. These signals have sufficient amplitude to be able to align the asbestos fibres in the electrical field created between the pins and electrodes.

The lower part of Fig. 3.3 depicts the signal processing system. The signal from the light sensor (photodiode) is pre-amplified directly in the optical probe and taken by a shielded cable to the main electronic unit where it is further amplified. It is then used for two purposes. First, after HF synchronous demodulation, integration and filtering, it is used to control the magnitude of light flux of the LED. Second, it is used to obtain information about the total dust and asbestos concentrations.

The signal is synchronously demodulated, which eliminates most of the interfering signals, both optical and electrical. The frequency of the signal is exactly one fourth of the HF transformer frequency, thus the full four cycles of HF interference from the electrodes are contained in every signal cycle. The integrator and filter are therefore able to remove this

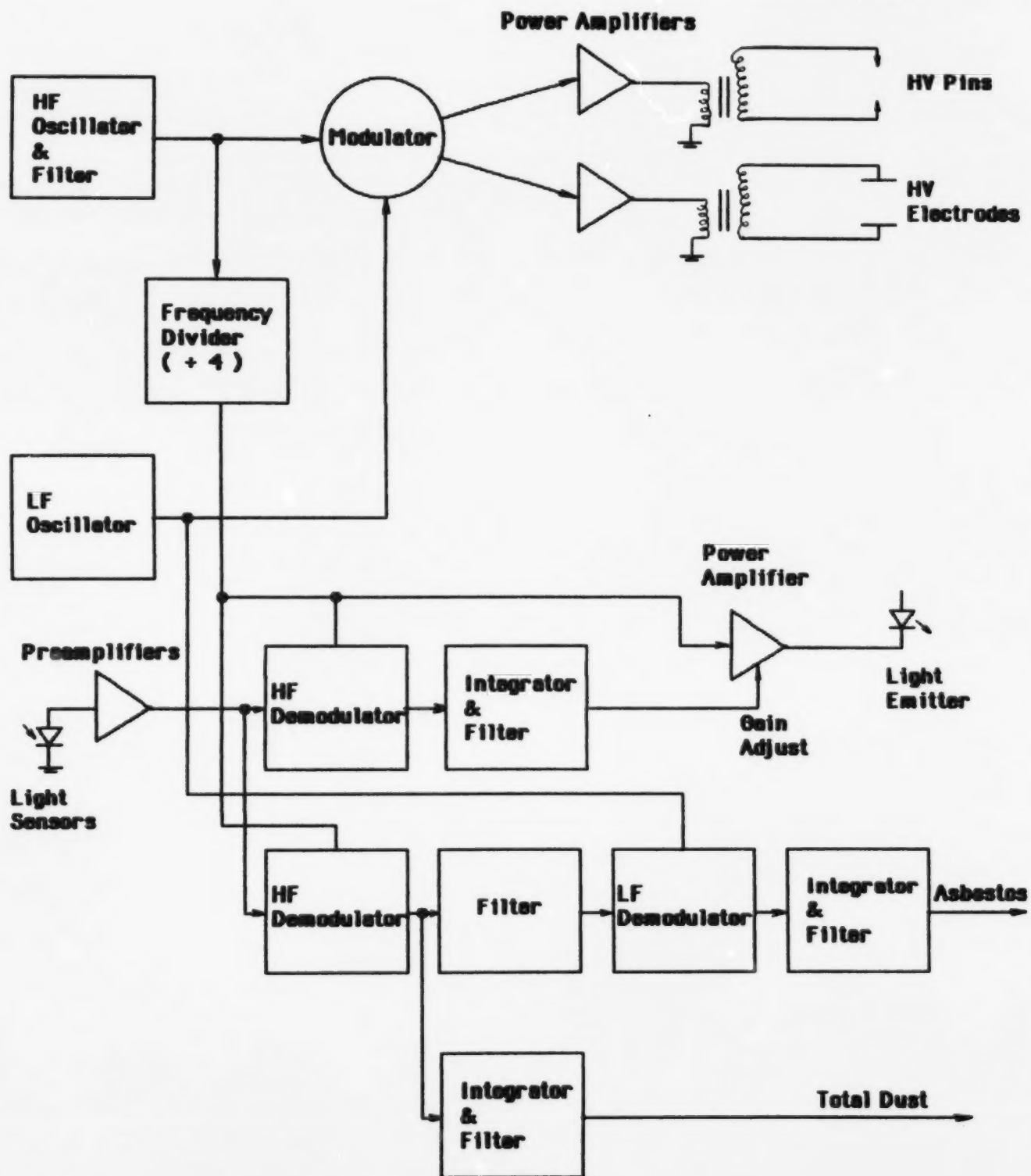


Fig. 3.2 Analog System Block Diagram

interference and produce a signal corresponding to the total dust concentration in the air.

Different signal processing is required to obtain the asbestos concentration information. The concentration of asbestos is proportional to the difference of signal levels during the time periods when pins and electrodes are activated. Another stage of synchronous detection is therefore employed. It uses a LF signal for detection (ie. the same signal that modulates pin and electrode voltages). The integrator and filter stage is used for the same reasons as described in the total dust case.

3.3 Test Results

Initially, with clean air in the chamber, a zero reading is set. The zero reading represents the noise level of the system. After injecting fibres into the chamber, both the asbestos and total signals increase and stabilize at a certain level. At this point, the air from the chamber is sampled on a membrane filter for a comparative microscopic analysis and counting. A large number of calibrations of this nature established the sensitivity of the instrument at better than 0.2 fibres/ml.

The asbestos fibres are injected into the chamber from the modified coffee grinder, with a 30 cm high vertical chimney attached to it, so that relatively modest quantities of suspended fibres are generated.

The microscopic analysis was done in house. To confirm our results, about 20 samples were sent for analysis to the Ontario Research Foundation.

The optimum region for the switching frequency was found to be between 6 and 10 Hz depending on the background dust present. In asbestos plants where the fibre concentration is relatively high compared to

the background dust, a frequency of 6 Hz is preferable. On the other hand, in situations when only a few fibres are present in a generally large concentration of dust, the optimum frequency setting would be around 10Hz.

Field testing was carried out in two asbestos plants. Both showed the concentration of asbestos within regulatory limits, exceeded on occasion during certain types of activity.

The system was demonstrated to CANMET and to guests from the US Bureau of mines, at a special meeting organized at the University of Toronto.

The first prototype described in this section, represents a very successful solution of the asbestos fibre monitoring problem, both in the choice of basic principles (optical detection, electrostatic alignment, free draft transport of sample) and in the realization of hardware. It can become a solid base for the construction of a more sensitive instrument, suitable for monitoring the present day limits of 0.1 to 2.0 fibres/ml. As we shall discuss later, a modern laser technology which allows for the use of a highly efficient optical system, can lead to the construction of a 0.05 to 0.1 fibre/ml instrument. This instrument would have the same sensitivity as the method of membrane sampling and will provide true in-situ real time results.

4.0 Microprocessor Based System Prototype

Encouraging results obtained using the analog system led to the design and construction of a microprocessor based instrument. Several objectives were set, before design commenced:

- a) Similar asbestos concentration sensitivity to that of the analog system.
- b) Low power consumption.
- c) Data logging capability (up to 8 days).
- d) Ability to function for a week without battery recharge.
- e) Computer communication capability for data discharge.
- f) Small, self-contained unit.

Photographs of the microprocessor based system prototype are shown in Figs. 4.1 and 4.2. A block diagram of the system is shown in Fig. 4.3. The microprocessor assumes the functions of a number of blocks of the analog system.

First, it generates all timing signals, thus replacing oscillators and frequency dividers. It has the ability to shut down most of the circuits and therefore significantly decrease the power consumption (a low power MC146805E2 CMOS microprocessor was used).

Light emitter, pin and electrode signals are generated by the microprocessor and are further amplified to obtain necessary power levels.

Light signal is preamplified and synchronously demodulated. It is then digitized using an integrating 10 bit A/D converter (ie. 1024 discrete levels can be distinguished). Both demodulator and conversion processes are controlled by the microprocessor as well. The duration of conversion is

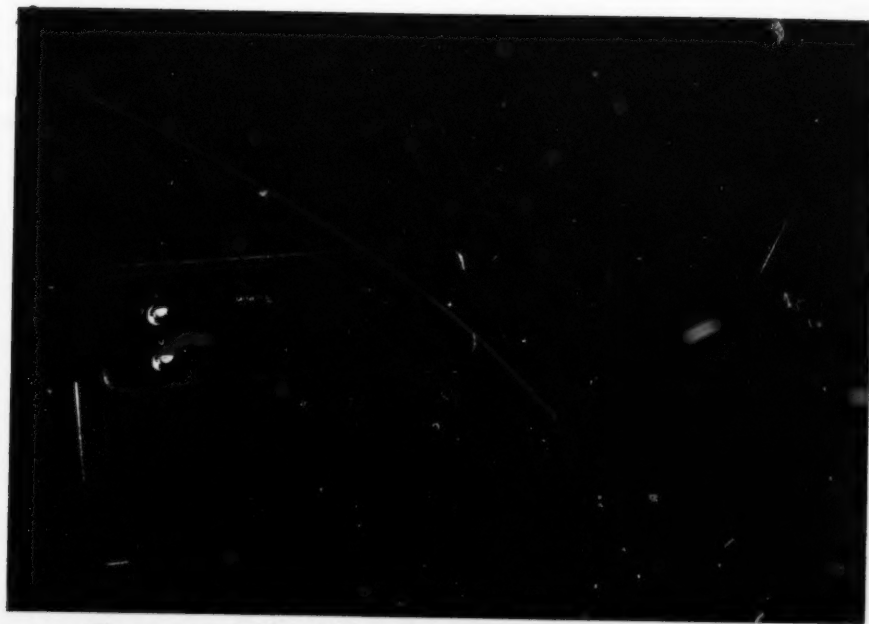


**Figure 4.1 Microprocessor controlled
Prototype**

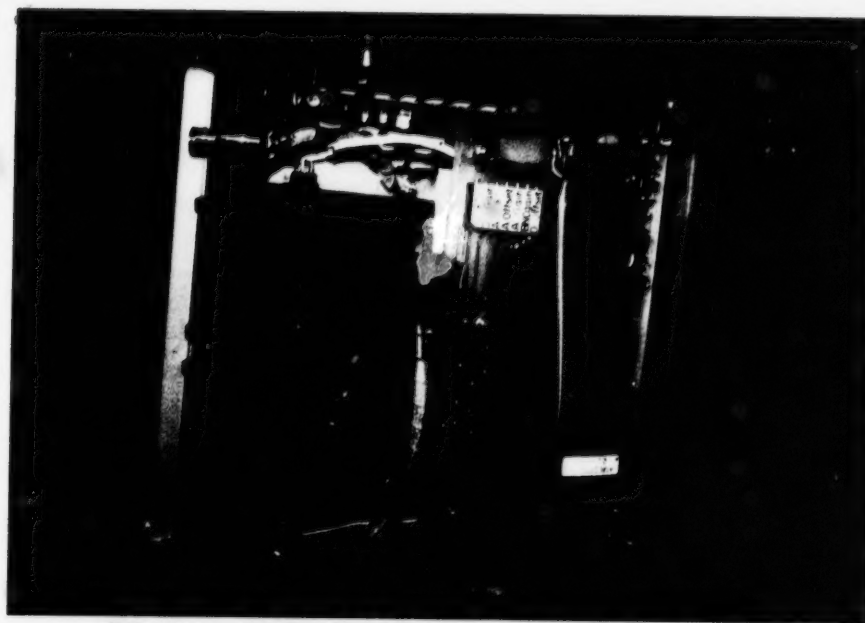


Figure 4.2 Interior Electronics

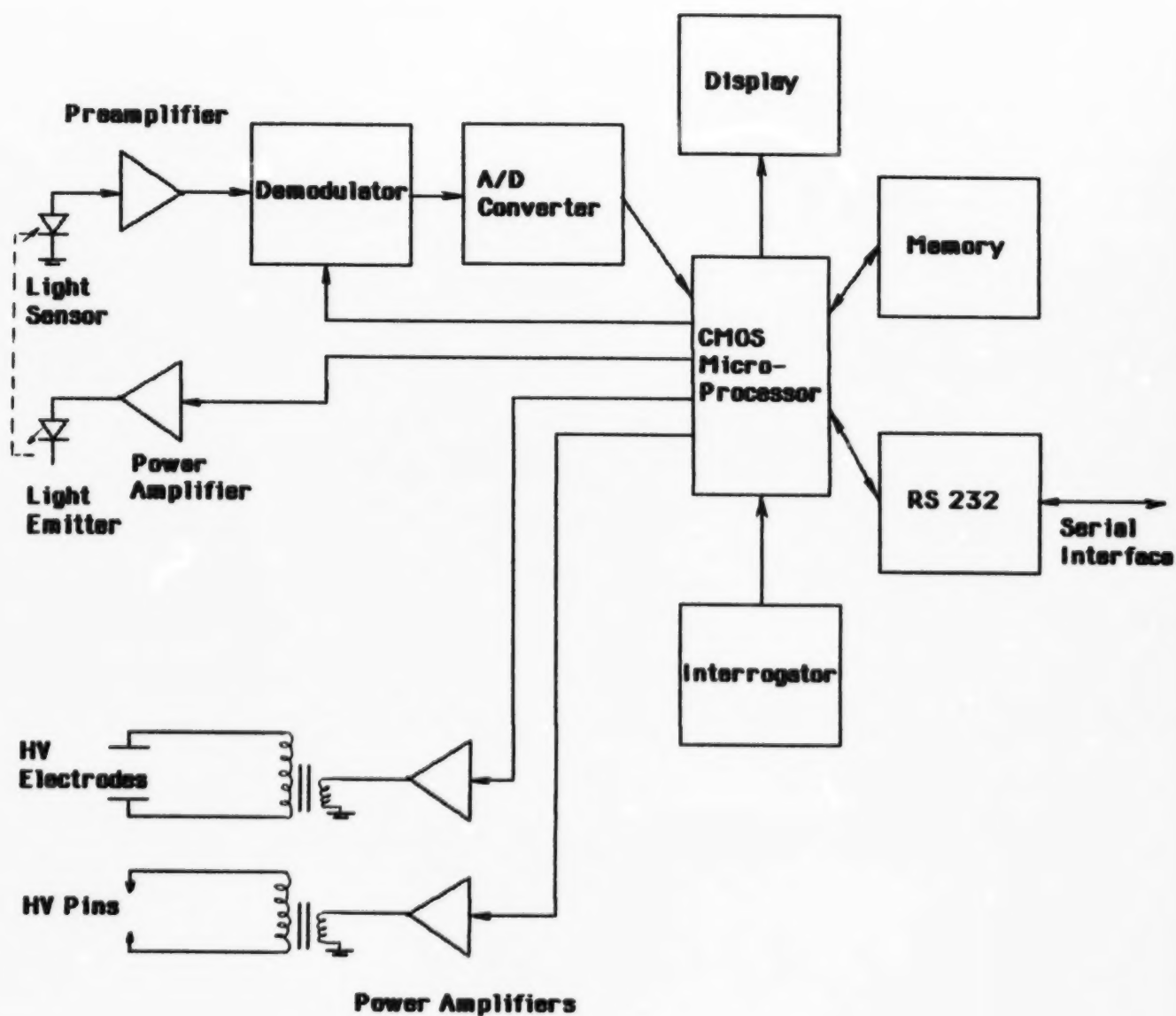


**Fig. 4.3 Microprocessor Based Instrument
Block Diagram**

chosen as a multiple of the mains 60 Hz period, thus eliminating 60 Hz electrical and 120 Hz optical interference.

The microprocessor controls a low-power LCD display, stores and retrieves data from CMOS memory, and discharges data via a serial communication line to a computer or printer. Instrument functions are controlled by a detachable interrogator box.

The original design stressed low-power, therefore all circuits (including analog ones) are designed to operate from a single +5 volt power supply, as opposed to the ± 15 V operation of the analog system. The output signals are therefore smaller in amplitude as compared with the analog instrument signals. Their ratio to the interfering signals coupled into the circuitry is therefore less, that is, the signal-to-noise ratio decreases. Also, the analog circuits are in close proximity to the digital circuits due to the compact design. Although shielding methods were used, interference from the digital circuits was not completely eliminated.

The instrument was originally operated in an intermittent mode. It was taking measurements for approximately 5 seconds then put in a "sleep" state for 55 seconds, during a 60 second cycle. This further decreased the signal-to-noise ratio due to the large off period. It was therefore decided to use a continuous mode of operation, together with digital integration (summation). This method still did not provide a sufficient signal-to-noise ratio, which is due to the fact that any digital method has to use digital samples (with all conversion errors, etc.), while analog integration uses a continuous signal.

A series of tests in a test chamber, using a reference measurement by membrane filters, established the sensitivity of this version as about 1.0 fibre/ml. In a preliminary test in the J. M. Asbestos mill in Asbestos, Quebec, it was determined that this sensitivity is inadequate for monitoring the present day mill environment.

5.0 Conclusion and Recommendations

The original asbestos monitor that we developed, has a sensitivity of around 0.2 fibres/ml. It appears that a present day monitor should have a sensitivity of better than 0.1 fibres per ml. This more stringent requirement arises from the new regulations, that specify a lower level of fibre concentration in many locations. Indeed, even in an asbestos mill, the typical concentrations do not exceed 1 or 1.2 fibres/ml.

Our monitor is a photon-noise limited device. The sensitivity limitation, noise, results from a very low level of light scattered by the fibres within the sample volume. As a general rule, in a photon-noise limited device, the signal-to-noise ratio increases with the square root of the collected light flux. In order to improve the present limit of 0.2 fibres/ml to 0.1 or 0.05 (4x), the collected light flux has to be increased 16 times. This would be a difficult task if we were to work with light emitting diodes, as in the final prototype.

Fortunately, during the past few years, an inexpensive, reliable, high-power semiconductor laser has been developed for the use in compact disc players (Sony, Philips). The cost of this device, purchased as a spare part for the CDP, including its power supply and an excellent optical collimating block, is under \$80. The extremely well collimated laser beam (its divergence is only diffraction limited) allows the use of much more efficient collecting optics, that can easily achieve the required improvement of 16x or more.

An optical system suitable for the application is shown in Fig. 5.1, along with a sketch of the proposed instrument shown in Fig 5.2. The basic idea here, is not to allow the scattered light to disperse too far, so that the

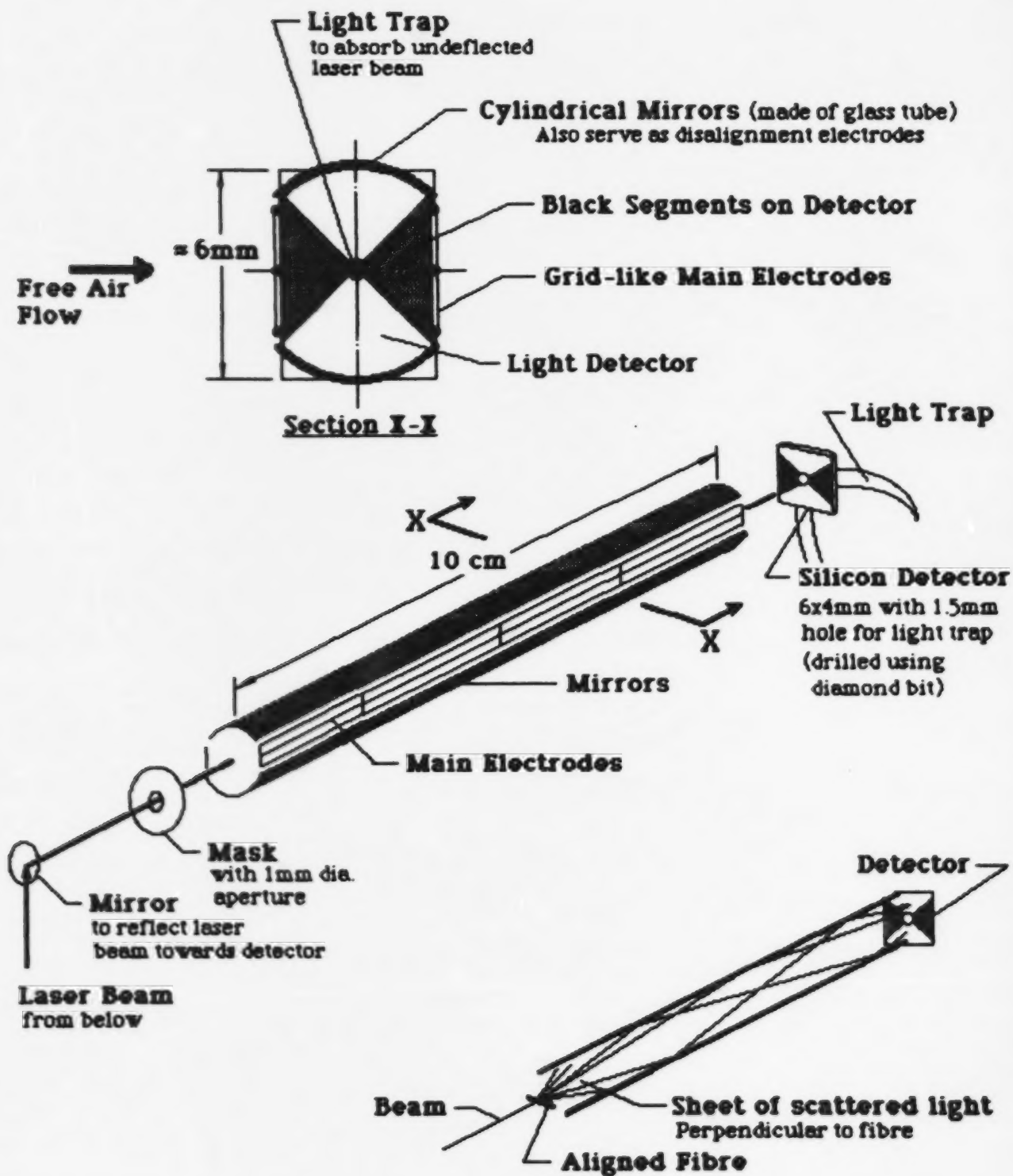


Figure 5.1 Proposed Optical System

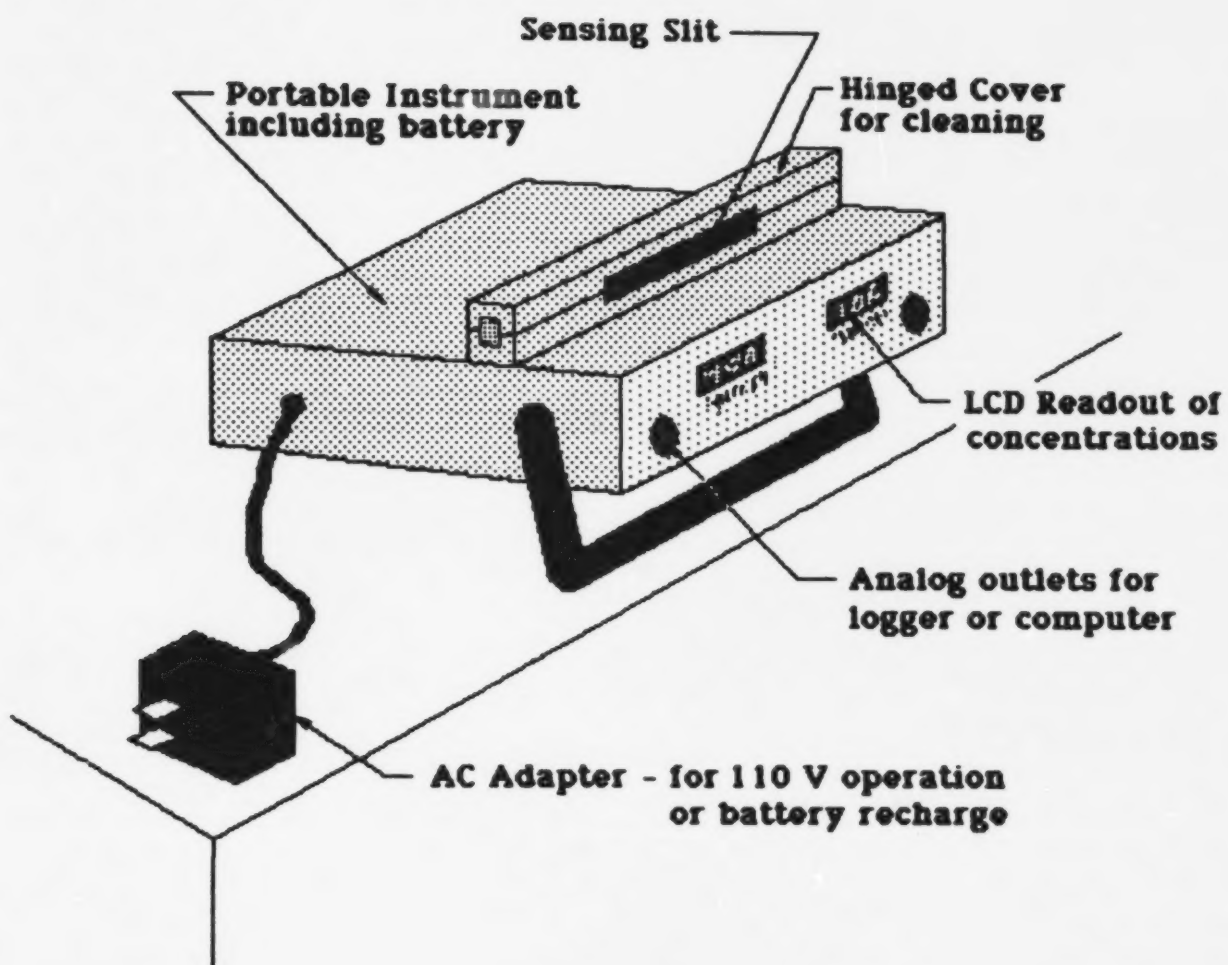


Figure 5.2 Sketch of Proposed Instrument

collection can be done by highly efficient and simple means. The parallel laser beam, focused on the entrance of the absorbing light trap, passes through a set of two long cylindrical mirrors (made of glass tube). A scattered light sheet, perpendicular to the aligned fibre, is directed by multiple reflections onto the detector. The detector has an opening through which the direct laser beam passes into the light trap. (We have the technology for boring detectors using diamond powder covered drill bits).

The sample space length (about 10cm) compares favourably to the present one (2mm). Also, the solid angle, from which the light is collected, is better. The optical advantage is expected to be about 100x, compared to the present prototype.

6.0 Proposal for Development of 0.1 fibre/ml prototype asbestos monitor

It is proposed to develop a new asbestos fibre monitor with a sensitivity limit of 0.1 fibre/ml, comparable to the limit of the filter sampling methods.

Duration of work: April 1, 1986 to Dec. 31, 1986

Financial proposal:

Salary of Opto-mechanical Engineer (4 months)	\$ 11,000
Salary of Electronics Engineer (4 months)	\$ 10,000
Salaries of Technicians (6 months)	\$ 9,000
Salaries total	\$ 30,000
Reduced overhead - 50% of salaries	\$ 15,000
Materials	\$ 5,000
Total proposed project cost	\$ 50,000

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